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TREAT FAST-NEUTRON HODOSCOPE: IMPROVEMENTS IN TIME AND MASS RESOLUTION OF FUEL MOTION*

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Abstract

The fast-neutron hodoscope at the Transient Reactor Test Facility detects fuel motion in thick opaque capsules during in-core destructive transient tests. Counts from several hundred detectors, each with rates up to a megahertz, are collected at intervals as short as a millisecond for up to tens of seconds. The large amount of data must be decoded, normalized, represented in suitable forms, and analyzed. A computer-controlled magnet disk data acquisition system has been installed which provides shorter data collection intervals, simplifies decoding, and permits immediate data analysis. Data normalizations and representations have been developed which significantly increase the dynamic range, yield sensitive quantitative indications of fuel mass motion, and render the data intuitively comprehensible. The improved hodoscope system performance level is demonstrated by results from a recent transient test, Pinex-2, which show the quantitative evolution of fuel mass motion from 1515 MW peak reactor power through a 1 MW post-scram radiation level.

Introduction

In support of the Department of Energy reactor safety program, the Argonne-West Transient Reactor Test Facility (TREAT) in Idaho conducts in-core destructive transient tests of encapsulated fuel bundles which simulate hypothetical accident conditions such as loss of coolant flow and transient overpower. The TREAT fast-neutron hodoscope was built to determine fuel motion in these tests by detecting fission neutrons emitted by the test fuel. (Optical detection methods cannot be used due to opacity of fuel capsules and coolant.) The hodoscope system consists of a collimator, bank of detectors, electronics, and equipment and programs to collect and manage the data.[1,2]

The detectors and new cross-focussed collimator are shown in Fig. 1. An area 6.6 cm wide by 122 cm high at the test fuel plane is viewed through 360 slots (10 columns × 36 rows) in a steel collimator by an array of Hornyak button fast neutron counters.[1] Reactor core elements between test section and collimator are slotted to allow an unobstructed view. The neutron source is remotely positioned in front of each detector for calibration. The gamma ray detectors are presently being used for clad blockage detection.[3] Prior to each transient test, the collimator is scanned horizontally in order to center the test fuel in the field of view and to provide detector normalization data. A post-transient scan is often conducted as well, in order to determine the final fuel disposition in more detail.[4]

In addition to the basic instrument shown in Fig. 1, equipment and programs for data acquisition and analysis are needed to produce the final product: a detailed report of quantitative fuel mass motion evolution for the transient test. New hardware and software in these areas are described in this paper which improve the TREAT hodoscope system capability for time and mass resolution of fuel motion, including a new magnet recording system, refined data normalizations and new data representations. The improved performance level is then demonstrated by results from a recent TREAT transient test.

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Magnetic Recording System

The TREAT hodoscope electronic system layout is shown in Fig. 2, including the linear amplification system, the digital photographic recording system[1], and the new magnetic recording system. The linear system is presently instrumented for 334 detectors, each of which may count at rates up to a megahertz at the peak power of the transient and down to a few hundred hertz after reactor scram. The photographic system, in which the counts are displayed on a binary lamp panel which is photographed by a high-speed camera, operates in parallel with the new magnetic system, providing a backup. The photographic system is capable of collecting counts from the array for tens of seconds at intervals as short as several milliseconds.

In the magnetic system, counts from the channel array are recorded on a fixed head-per-track magnetic disk, with sampling intervals down to 0.52 msec and a capacity of 8192 samples for the full complement of detectors. If only 88 scalers are used, a sampling interval of 0.13 msec is possible, with a capacity of 32768 samples. A magnetic tape simultaneously samples the data at ∿ 30 msec intervals (providing further redundancy) and records post-scram data (because of its longer recording duration). System checkout and parameterization, printing and plotting of data for immediate analysis, and transfer of disk data to magnetic tape (for further refined analysis at ANL) are accomplished under computer control. The magnetic recording system provides improved time resolution and computer-compatible records. The possibility of data loss from handling, exposing, and developing photographic film is eliminated, as is the laborious film scanning.

The scalers, scaler controller, and disk controller in the magnetic recording system are built into CAMAC crates, which were used because of the convenient bus structure. However, CAMAC protocol is not used. For this specific application, data format and control functions are simple and fixed, so that the execution time and board space overhead of CAMAC coding could be eliminated.

The 12-bit scalers are grouped into 22 modules per crate, 8 scalers per module, except that one module contains time from the IRIG and BCD timers, obtained through the timer/interlock. The scalers receive pulses from the detectors through the fanout and, upon command from the scaler controller, deposit accumulated counts (and time, in the case of one module) simultaneously in latches, which are read serially two at a time (over a 24-bit line) by the controller. The latch, store, and reset operations are completed in ∿ 1 usec. Presently two crates are used (352 channels), but more can be added.

The scaler controller is a direct-memory-access (DMA) device on the minicomputer bus and transfers data simultaneously to computer memory and the disk controller (data is not transfered to the computer unless it is ready). To avoid excessive bus latency time, the scaler controller is maintained as bus master of the computer bus during the entire data transfer. The scalers can be read in half-crate (88 channel) segments. Code for the designated half-crates is keyed in on the teletype under program control and deposited in a scaler controller register prior to the transient. Compatibility between the 16-bit computer word length and the 24-bit CAMAC bus is maintained by using a 48-bit data register, containing data from four scalers, which is multiplexed into three 16-bit words. Data is fed to the disk controller as fast as the disk can be written. When data from all designated scaler half-crates has been read and the disk is ready to be written again, the scalers are latched.

The disk controller receives data from the scaler controller into a 24-bit shift register and writes the disk, if enabled. The disk clock rate of over 9 MHz controls the write operation. The disk is enabled for the transient mode, but disabled for the scan mode, for which the data is written on magnetic tape only. The disk controller also sends status information to the scaler controller. The disk is written until it is full. After the transient, the disk data may be read through the disk controller out to the computer through a 16-bit shift register in DMA mode. The duration of disk recording is extended by interlacing (skipping) sectors. The interlace factor is keyed in on the teletype under program control and deposited in a disk controller register prior to the transient.

The head-per-track disk has 256 tracks of 512 sectors each, 273 bits per sector, and spins at 60 revolutions/sec. Twenty-two hodoscope channels (264 data bits) are written in each sector. The sampling interval t depends on the number of designated half-crates h and the interlace factor i (i = 0 to 7) as

$$t = 0.1299\ (2^{i})\ h \qquad (1)$$

in msec, while the number of samples n of designated half-crates on the disk is given by

$$n = 32768 / h \quad , \qquad (2)$$

and the disk recording duration T is obtained from

$$T = 4.267\ (2^{i}) \qquad (3)$$

in seconds. There are some anomalies in t, including a 40 μsec delay when the track origin is passed and on additional one-sector (32 μsec) lapse when the track origin is passed without switching tracks (occurs when i>0). However, these anomalies are small compared to t and the actual latch times are always recorded in each sample.

The magnetic tape controller is a DMA device on the computer bus and interfaces to a standard 9-track, 75-ips, vacuum-column tape drive. The magnetic tape drive is used to load all programs (all of which are stand-alone) into the computer, to record pre- and post-test scan data, to provide redundant data recording during the transient, and to provide data copies for transmission to Argonne-East for refined processing and analysis. The minimum sampling interval t' for the tape unit is, in msec,

$$t' = 18 + 2h \quad . \qquad (4)$$

During the transient, the scaler data sent to computer memory is written to tape, but since the computer bus is hung for time t, the tape will only record every jth sample which is written to disk, where

$$j = \langle (t + t') / t \rangle \qquad (5)$$

and <...> indicates that if a non-integer value is enclosed in the braces, it is to be increased to the next integer. This data is called file 1. After the disk is full, the scalers are latched by program according to Eq. 1 but the read sample interval is the larger of t and t'. The tape continues to record data until end-of-tape is encountered. This data is named file 2. The tape then backspaces far enough (but not so far as to overwrite file 1) and records the disk data, which is transferred to computer memory by the disk controller. This data is termed file 3. Usually a 1200-ft reel of tape is enough to contain files 1 and 3 and a substantial portion of file 2.

In addition to the redundant recording already mentioned, a number of hardware and software interlocks and indicators provide protection against data loss in the relatively complex hodoscope system by helping insure the transient does not proceed until all crucial subsystems are ready. Software protection includes program tests and teletype checklists and messages. There are panel lights in the hodoscope room indicating status of crucial subsystems, as well as a hodoscope-system-ready light in the hodoscope and reactor control rooms.

The timer/interlock chassis provides serial interlocking of crucial subsystem status indicators with the magnetic-system and camera-system ready-lines to form the hodoscope system ready-line. This chassis also receives the start pulses from the reactor control room for the magnetic system and camera system (the start pulse for the latter precedes that for the magnetic system to allow for camera start-up). In addition, the timer/interlock chassis relays the IRIG time and provides the hodoscope BCD time to the first scaler module. The IRIG time (0.1 msec precision) is common to all instrumentation, including test train thermocouples, flowmeters, and pressure gauges and allows intercomparison of results, while the BCD timer (0.01 msec precision) provides greater precision for fuel motion analysis.

The minicomputer provides the magnetic recording system with all necessary program control during system checkouts, pre- and post-test scans, and transients. Programs are also provided for checking data validity by inspection of printouts and time plots produced on the electrostatic printer/plotter, which has 28 dot/cm resolution and prints at 8 lines/sec. Programs are now being developed to provide less refined versions of some of the data normalizations and representations discussed in the next section which are used at Argonne-East. This will allow immediate on-site fuel motion analysis of a relatively crude form in those cases where it is desireable.

Data Normalizations and Representations

Certain normalization operations must be performed on the raw hodoscope data before it can be said to quantitatively provide fuel mass motion: division by time interval, reactor power, and relative channel efficiency; compensation for spatial flux variation; and correction of nonlinearity with respect to reactor power. Hardware and software improvements in these areas are significantly increasing hodoscope dynamic range and rendering the data more quantitative with respect to fuel mass. Also, new and more refined data representations have been developed which yield more sensitive quantitative indications of fuel mass motion and make the data intuitively comprehensible, despite the large amount of data and the statistical fluctuations.

The Hornyak button detection channels exhibit a supralinear count rate response with respect to reactor power which varies amoung channels.[1] This effect not only reduces the capability to provide quantitative fuel motion information but also reduces the dynamic range of the data by causing premature deadtime saturation. The effect has been minimized by interposing lead filters in front of the detector array, as shown in Fig. 1. A program has been developed which provides correction factors a and θ for supralinearity and deadtime of each channel by a minimum variance fit of a model to reactor power. The correction formula is

$$c' / (1 - c'\theta) = c + ac^2 \qquad (6)$$

where c' is the measured count rate and c is the corrected count rate.[5]

Recent experiments suggested that the supralinearity effect could be reduced by a shortening the Hornyak buttons to one-half their length. All Hornyak buttons have now been shortened, which has reduced the typical a value from ∿ 30 μmsec to ∿ 8 μsec, a significant improvement, particularly for high count rates. A new compensated ion chamber flux monitor, shown schematically in Fig. 2, has been wired to two scalers for 24-bit precision. This will allow more precise and easier power normalization and supralinearity correction. (Previously, power profiles from an external 12-bit monitor have been manually entered into the correction programs).

After pre-test detector calibrations and post-test supralinearity corrections are performed, significant differences in relative efficiency among channels remain. Also present is significant axial flux variation. A program has been developed which provides efficiency correction factors yielding uniform response over the array (i.e. uniform background and fuel profiles), as desired for quantitative fuel mass motion analysis (at least to first order). The program first performs a minimum variance fit of the array count rates to a two-dimensional model of the fuel and background, to determine signal-to-background ratio and locate the fuel bundle precisely. The program computes the necessary efficiency multiplier for each channel to give uniform fuel pins and a constant background. The use of pretest scan data in conjunction with this program to provide some constraints on the fit is being tried, in an effort to increase accuracy.

From knowledge of the output of the efficiency-correction program, the reference power normalization, and the total test fuel mass, a single mass calibration factor can be derived which converts power-normalized count rates (with background subtracted) to fuel mass. However this factor is used with caution, since no account has been taken of self-shielding, self-multiplication, flux depression, and attenuation effects in its derivation. Nonlinearities resulting from these effects undoubtedly occur, particularly during gross fuel motion. Nevertheless this calibration factor in most cases appears to lead to a reasonable first approximation of fuel mass motion. The nonlinear effects mentioned are under study.

The mass calibration factor has been used to provide mass and mass change scales in Fig. 3, which illustrates some new data representations obtained from a 39 dot/cm electrostatic printer/plotter. Each grid square represents a region at the test plane viewed by the hodoscope, and every other row and column are numbered to the right and top. The fuel pin location (single-pin test in this case) is the narrow outline in the center of the arrays. It should be remembered that ratio of width to height is considerably enlarged in these representations, the horizontal and vertical interchannel spacings being 6.58 mm and 34.54 mm respectively.

The first representation shown in Fig. 3 is called a symbolic mass (integral) hodograph. Symbols are used instead of continuous gray levels to represent fuel quantity. The sizes of the black symbols indicate the amount of mass viewed by each hodoscope channel. (Channel overlap causes channels adjacent to, but not aligned with, the fuel pin to register some response.) The smallest dots represent masses between 0 and 0.5 g. The picture here, with power normalized count rates averaged over 0.40 sec about 10.20 sec transient time, is that of a uniform pin (with background subtracted), indicating no significant fuel motion.

The second representation shown in Fig. 3 is termed a symbolic mass-change (difference) hodograph and indicates the fuel mass motion which occurred between 10.20 and 10.61 sec (averaged over 0.02 sec). The empty 'x' squares are inoperative channels. Mass changes between -0.2 and 0.2 grams are not shown, being represented by the 'gray' squares. The sizes of the black symbols indicate the amount of mass increase seen, while the sizes of the white symbols show the amount of decrease. Fuel is seen to be ejected above the pin from the lower central axial region, with a small amount accumulating at the bottom of the pin. The entire motion is small compared to the ∿ 165 g mass of the pin, and a small amount of statistical noise can be seen, due to the relatively small normalized count rate differences. The sum over columns 4-6 for each row indicates the overall axial motion, while the sum over rows 1-36 for each column shows the overall transverse motion. The transverse motion consists of an inward movement toward the pin center (in this case, possibly fuel melting along the sides of the central void, flowing into the void, and moving upward, although spatial resolution is not great enough to see this directly).

The same type of information as presented in Fig. 3 is also available as digital-array table printouts of normalized count rates and count rate differences, using a different program. This program has options which provide a statistical analysis based on count statistics and significance thresholds based on this analysis. These digital arrays complement the hodographs, being more precise and more sensitive than hodographs, but less appealing to the eye and providing less intuitive comprehension of the motion. Simultaneous plots of normalized count rates vs. time, averaged over suitable time intervals and array regions, are also useful complementary representations, particularly when count rates are low and judicious time and region averaging are required, or when event initiation times and time correlations are important.

TREAT Test Pinex-2

Pinex-2 was a TREAT transient overpower test run in January 1978 for Hanford Engineering Development Laboratory and Los Alamos Scientific Laboratory. A single preirradiated pin 0.864 m long with a 5.84 mm OD and a fabricated 0.81 mm diameter hollow axial annulus was positioned in a static NaK-filled autoclave. The magnetic recording system parameters were chosen for this transient so as to insure that post-scram fuel motion would be recorded on disk, while utilizing the full complement of channels. Thus h = 4 and i = 2 were chosen in Eqs. 1-5, leading to a disk sampling interval of 2.08 msec and a disk duration of 17 seconds.

Six fairly well-separated fuel motion events were observed. Their parameters are given in the following table. The masses shown were obtained from the calibration factor discussed in the preceeding section. All of the normalizations and representations discussed in that section were applied. A reference interval 10.0 - 10.4 sec, before significant fuel motion was observed, was chosen and is shown in Fig. 3 as a symbolic mass hodograph.

Events I and II, beginning at 10.51 and 10.55 sec, were relatively minor and involved expulsion of 0.3 - 1.5 g and 0.7 - 1.7 g, respectively, of fuel above the test pin. These events appeared to be accompanied by mild bowing of the pin, which was observed to be present throughout the remainder of the transient. Event III, initiating at 10.562 ±0.004 sec, consisted of voiding of fuel in the axial central region of the pin, accumulation at the bottom of the pin, and ejection of 5.3 ±1.3 g above the pin into the plenum, followed by voiding of the top region of the pin and accumulation in the axial central region. One of the symbolic mass-change hodographs for this event is shown in Fig. 3 as an example.

Event IV, which was similar to event III, began at 10.76 ±0.02 sec and involved movement of fuel from the bottom and central regions up through the pin, resulting in expulsion of 10.2 ±4.2 g above the pin, about 3 g of which remained in the reflector (the rest went up into the plenum). Event V, which started at 11.30 ±0.03 sec, was also similar to event III, except that fuel was not expelled above the pin, but only reached the top region of the pin and subsequently moved back down to the central region. Event VI, which initiated at 11.71 ±0.05 sec, was again similar to event III, and resulted in ejection of 13.4 ±3.5 g above the pin, of which 4.3 ±3.5 g remained in the reflector region (the rest moved back down into the top portion of the pin).

It is estimated that at the end of the transient approximately 21 ±7 g of fuel had been expelled upward from the test pin. Clad failure did not appear to occur and fuel motion was basically restricted to axial motion in the fabricated hollow annuli of the pin and upper structure. The reactor power level at the initiation time of each event is shown in the table. For transient test Pinex-2, it is seen that the quantitative evolution of fuel-mass motion has been demonstrated from 1515 MW peak power through a 1 MW-post-scram radiation level.

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PARAMETERS OF SIGNIFICANT PINEX-2 EVENTS

Event	Power (MW)	Initiation Time (sec)	Fuel Expelled from Pin (g)	Fuel left in Reflector (g)
I	1200	10.51	0.3 - 1.5	
II	1500	10.55	0.7 - 1.7	
III	1515	10.562 ±0.004	5.3 ±1.3	
Scram		10.57		
IV	11	10.76 ±0.02	10.2 ±4.2	3
V	2	11.30 ±0.03		
VI	1	11.71 ±0.05	13.4 ±3.5 (9.1 g re-entered pin)	4.3 ± 3.5
End of Test		13.0	21 ± 7 (net)	4.3 ± 3.5

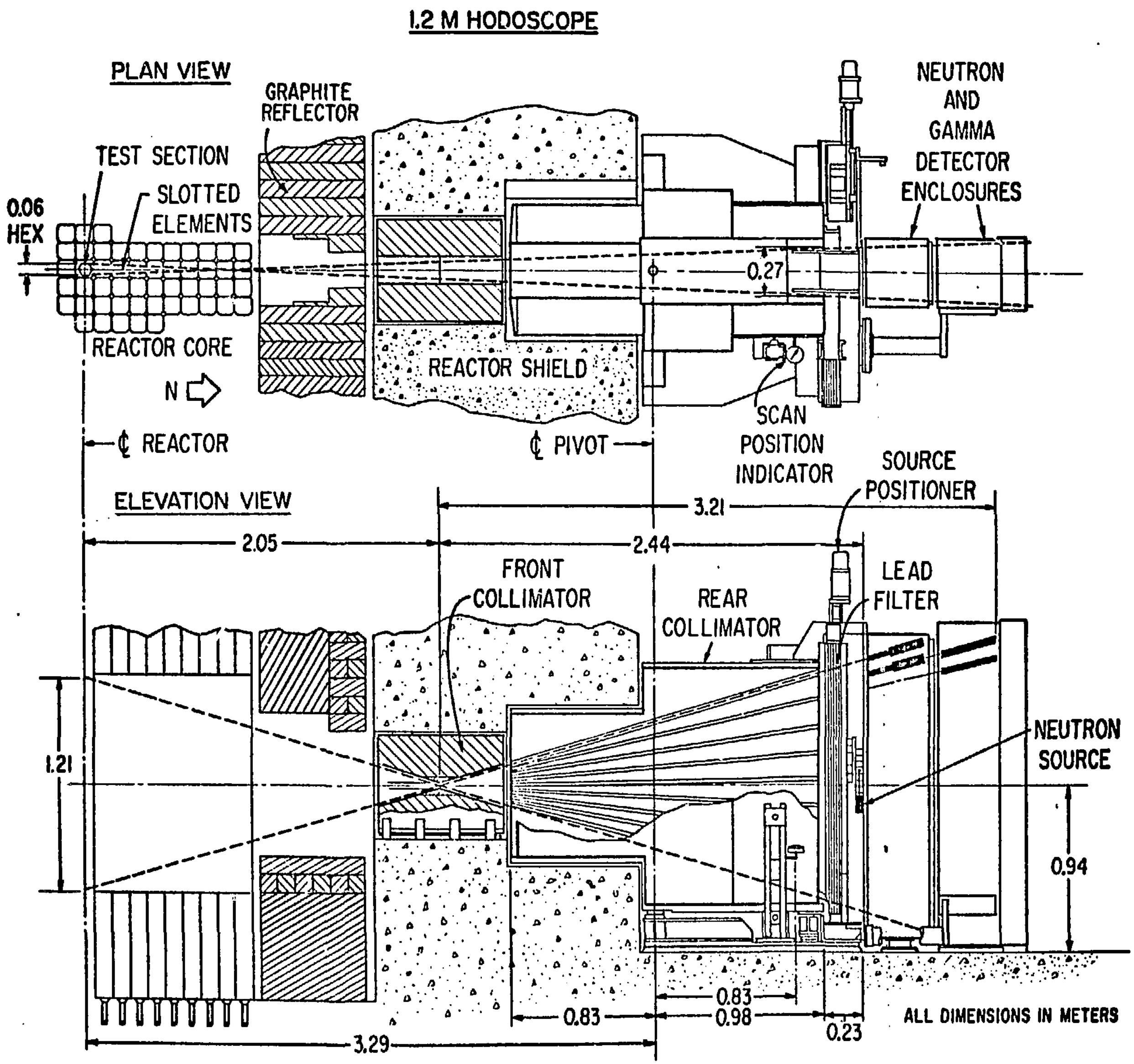

Fig. 1 Elevation and plan views of the TREAT cross-focussed hodoscope collimator. Only a representative number of the full complement of 360 detection channels are shown.

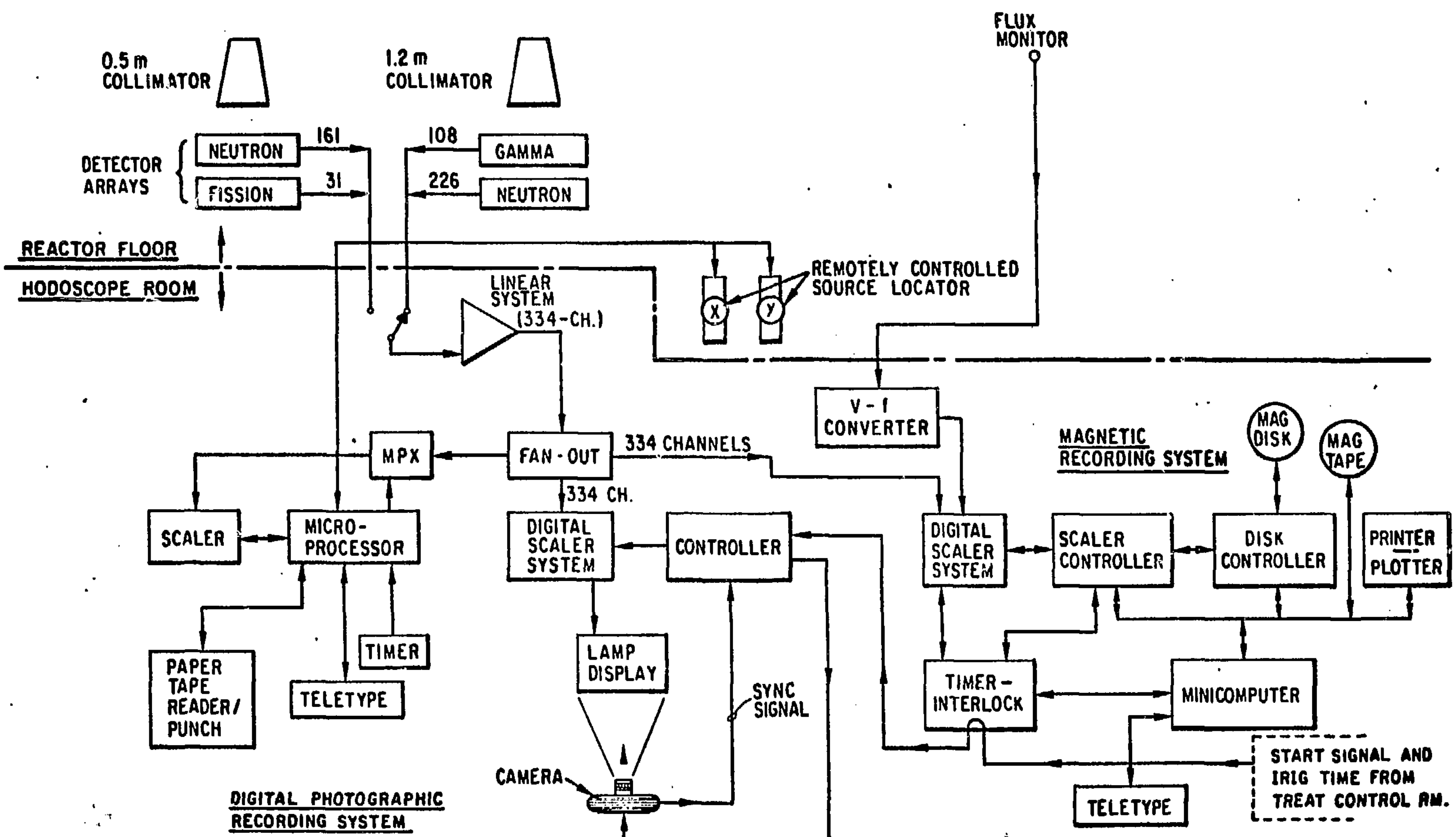

Fig. 2. Layout of the TREAT hodoscope electronics systems.

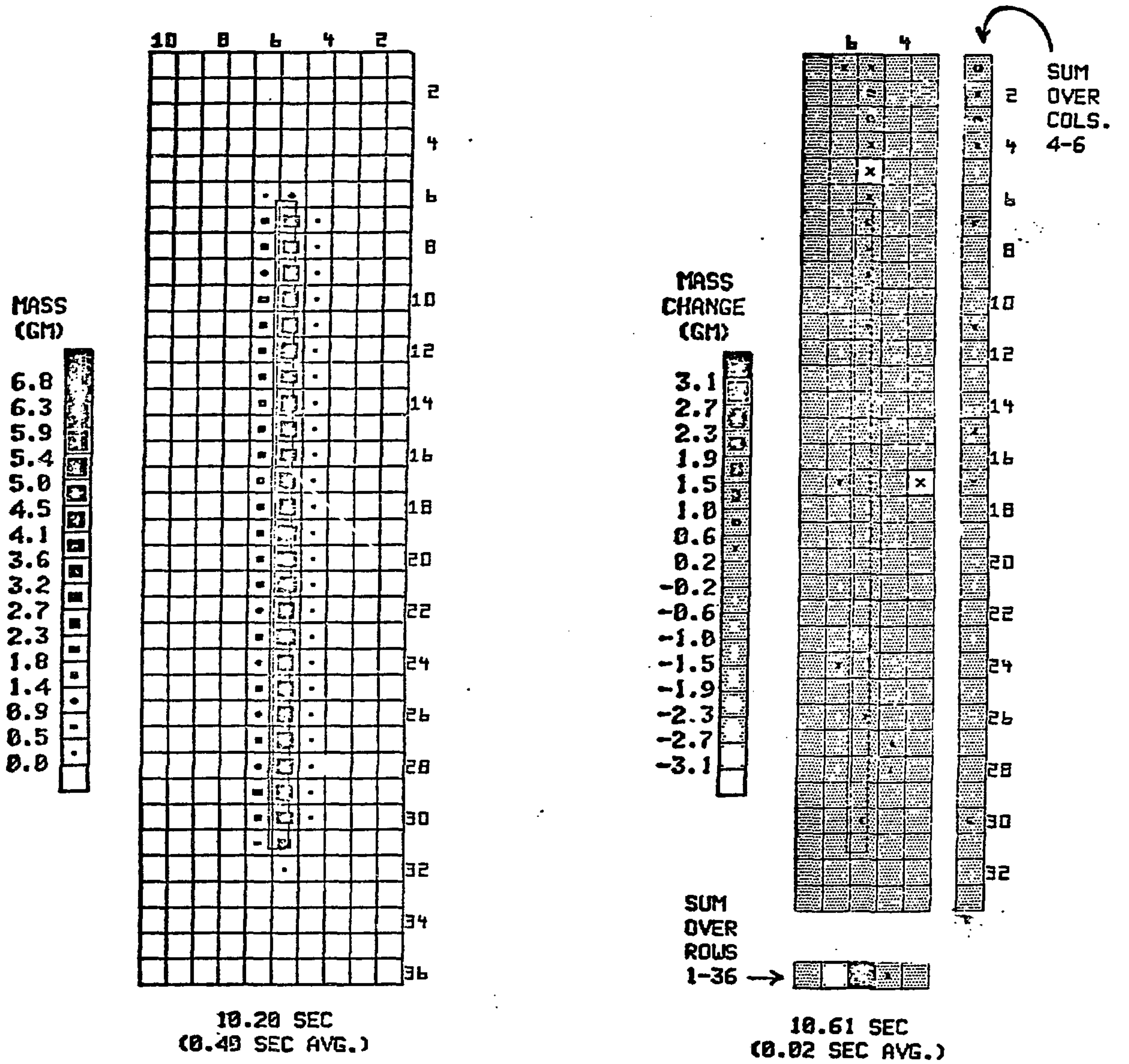

Fig. 3. Mass and mass change symbolic hodographs for TREAT test Pinex-2. The mass hodograph indicates fuel disposition at 10.20 sec reference time, while the mass change hodograph shows mass motion occurring between 10.20 and 10.61 sec.